A COMPARISON OF TWO STEREOLITHOGRAPHY RESINS

An Honors Thesis (HONRS 499)

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Expected Date of Graduation

December 1992

ACKNOWLEDGEMENTS

The author would like to acknowledge and thank the following people for their assistance in conducting the research and experiments associated with the research: Mr. Steve Riley, Delco Remy; Mr. Bill Johnson, Delco Remy; Mr. Bob Claypool, Delco Remy; Dr. Gerald Steele, Ball State University. Without their generous contributions this project would not have transpired.

ABSTRACT

The researcher has done a project on the new technology of stereolithography (SLA). This technology uses a 3-D model of a part to rapidly produce a prototype part using a laser to solidify a liquid resin. This procedure gives the customer the chance to see a product in hours instead of months. The material, however, is too brittle for tests that involve stress on the part to be conducted. It was the intent of the research project to find the right combination of cure time and variable settings which would yield the maximum strength of the material. Since the project was for Delco Remy, the researcher compared a GM resin with a suggested resin from the SLA manufacturer. Because of understandable reasons with competition in the automotive industry, the actual names of the resins have been withheld from the report. ASTM test standards were used in the tests that were conducted.

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CHAPTER 1

COMPANY HISTORY AND INTRODUCTION OF PROBLEM

INTRODUCTION

Way back before the turn of the century, Frank and Perry Remy had an idea. The idea of establishing a home wiring business, the Remy Electric Company. The Remy brothers set up shop in Anderson, Indiana and began to have other ideas. Capitalizing on the fact that eleven of the nation's earliest car manufacturers were in Anderson, the Remy brothers soon changed their focus to that of supplying magnetos to the rapidly growing auto industry. As the industry grew, the magnetos became obsolete. The Remys saw a need to adapt and they did. In 1911, the first cranking motor was produced. Shortly thereafter, the company's product line was expanded to include battery ignitions, cranking motors, generators, and distributors. In 1926, the Remy Electric Company, now a division of General Motors, consolidated with the Dayton Engineering Laboratories Company (Delco) and became Delco-Remy. The once bitter rivals now become one and the production of batteries soon began. Because of the enormous competition in the automobile industry today, Delco Remy has had to stay abreast of all the new technology that has come along, in order to use that technology to their advantage.

PROBLEM STATEMENT

One of the newest and most exciting technological advances to come along is stereolithography. This device utilizes a computer controlled laser to solidify a liquid polymer material as directed by a three dimensional model. Recently, Delco Remy purchased an SLA machine and are now trying to produce parts to assist in the layout, design, and functionality of plastic parts. However, these parts are too brittle to be put under stress. It was the intent of this study to examine two liquid resins: the first was a GM resin; the second was recommended by the manufacturer of the stereolithography machine. To compare the physical and mechanical properties and determine how to maximize the strength of the two resins. The researcher looked at tensile strength, displacement of material, stress at break point, strain, and elongation.

PURPOSE OF STUDY

By conducting the study, information was intended to be gained to assist in the design stage of a part so that the cost of a design can be decreased. The greatest costs for new parts in the automotive industry are in the design and testing phase due to redesign of the part before final approval. Seventy percent of the total cost of a part comes from the design phase, which is usually only 5 percent of the budget for the part. By using the SLA technology, this costly step in the process is intended to by decreased, since the SLA machine can produce a part for a fraction of the cost of designing tooling to produce the same shaped part.

LIMITATIONS

There were several limitations to the study. The most prominent was the availability of the machines at Delco Remy in the times that the researcher needed their use. Delco Remy used the SLA equipment regularly. Also the physical test machines were scheduled for work as they were needed by engineers. Other limitations were the limited time the researcher had to devote to the project because of a 17 hour class load and a 20 hour work load per week during the second semester. A set back from the start was the heart attack of Dick VanSkyock since he was to assist in the research.

HYPOTHESIS

1. There will be no significant difference in the tensile strength between the GM material and the manufacturers material using the ASTM D638 test with the Instron tester in the Delco Remy physical test lab.

REVIEW OF RELATED LITERATURE

RESEARCH

With emerging prototyping methods, both designers and manufacturing engineers can see and hold physical models of part designs in hours instead of weeks. They can spot and fix flaws fast. At least 16 different systems are in development[1]. Most rapid prototyping systems use a layer manufacturing process. They electronically divide a 3-D CAD model of a part into thin horizontal cross sections and then transform the design, layer by layer, into a physical model. 3-D Systems Inc., the first firm to offer a production system, has already sold more than 240 of its StereoLithography Apparatus (SLA)[2].

Stereolithography combines four technologies: laser, optical scanning, chemistry, and software. The first step is to create a 3-D solid model in a CAD system. Next the CAD model is converted into a format the SLA can read. The SLA slice computer divides the file into cross sections that range from 0.005 to 0.30" thick[3]. The data representing each layer is used to control a beam of ultraviolet light that draws the shape of that layer onto the surface of a bath of photosensitive resin. The resin solidifies wherever the light strikes, resulting in a solid layer of the CAD design. Successive printings of cross sections, each adhering to the preceding layer, create a part. Postcuring involves applying intense long wave UV light to solidify the uncured liquid trapped in the honey-comb like part cavities. A secondary operation is to heat treat the prototype part to try to strengthen the part.

Although stereolithography can provide a bonanza of benefits for companies, the system has some limitations. These include size limitations,limited resolution, possible warpage and shrinkage, and most importantly, material brittleness. The latter is what the researcher is looking to try to maximize the material strength.

The SLA machines use different types of materials depending on their size. Most, however, are an acrylic polymer of some type which becomes hard but brittle after solidifying. This is a major limitation in doing testing on a designed part. Also, when the cost of material is addressed at $300-$350 per gallon one can see why a more durable material is desired. A "more durable polymer" was ranked at the top of most-wanted-improvement list by customers[4]. Also, a more fluid polymer needs developed, because the current material has the consistency of molasses making cleaning the tank between changeover a time consuming effort.

PROPOSAL FOR SOLVING PROBLEM

DESCRIPTION

To solve the brittleness problem of the resin the researcher wanted to examine how the different settings on the SLA machine would effect the tensile strength of the material. The steps involved in doing the research were to run the SLA machine making tensile test bars with different variable settings on the machine, and cure them for different lengths of time. Then test the samples, plot the data, and analyze the results. Next, change the material in the SLA machine and run the same variable changes on the GM resin. Lastly, compare the results of the resins to each other as well as finding the best settings for that specific resin. The variables that were looked were the following:

1. The X-hatch spacing was ran at .28 millimeters, which is the system default, then it was ran at .50 millimeters. This variable specifies the distance between cross section vectors drawn parallel to the X axis.
2. The Y-hatch spacing was ran at .28 millimeters, which is the system default, then it was ran at .50 millimeters. This variable specifies the distance between cross section vectors drawn parallel to the Y axis.
3. The X and Y skin fill was set with one at .1 millimeters and the other at zero. Then the values were reversed to look at the effect of how the laser solidifies the part. The skin fill specifies the distance between skin fill vectors drawn parallel to the X and Y axis respectively.

With the value set at zero the SLA machine generates no skin fill vectors in that direction.

4. The cure time was changed from the setting of 99 minutes, which Delco Remy had used as a default since that was as long as the timer on the UV machine could be set at one time, to 45 minutes to examine the effect the time in the cure stage had on the parts.

5. The delay time was also looked at. This is the time the parts sat at ambient room temperature before they were put into the UV machine. At Delco Remy the parts will be ran during lab hours in which a technician can immediately put them in the UV oven or the parts are ran during the evening causing the parts to be exposed to room temperature for approximately 14 hours. Therefore the researcher choose zero and 14 hours for the two setting on delay time.

TESTS NEEDED

The test needed to complete this project was the tensile strength test. The test was conducted at Delco Remy under the same conditions using the same machine for the test. The Istron tensile tester was used to test all the samples, so the same software was used to eliminate as much possible error as the researcher could.

TEST MATRIX

The test population for each group was six tensile test bars. The SLA machine's capacity was theoretically a 10 inch cube, and six test bars were all the machine could produce in one run. A single run to produce a test group would take three and a half hours plus the cure time. There were seven groups made for each resin tested. Each group had one or two variables changed from the two Delco Remy normal SLA settings. For convenience the test groups will be referred to as group A through group N. The following test matrix shows the variables of each test group. For additional information on the test groups see the computer printouts of the settings for each group in appendix B.

Group #	X Hatch	Y Hatch	X Skin Fill	Y Skin Fill	Cure Time	Delay
A	.28 MM	.28 MM	.10 MM	0.00 MM	99.9 Min	0 Hrs
B	.28 MM	.28 MM	.10 MM	0.00 MM	99.9 Min	14 Hrs
C	.28 MM	.28 MM	.10 MM	0.00 MM	45.0 Min	0 Hrs
D	.28 MM	.28 MM	.10 MM	0.00 MM	45.0 Min	14 Hrs
E	.28 MM	.28 MM	0.00 MM	0.10 MM	99.9 Min	0 Hrs
F	.50 MM	.28 MM	.10 MM	0.00 MM	99.9 Min	0 Hrs
G	.28 MM	.50 MM	.10 MM	0.00 MM	99.9 Min	0 Hrs
H	.28 MM	.28 MM	.10 MM	0.00 MM	99.9 Min	0 Hrs
I	.28 MM	.28 MM	.10 MM	0.00 MM	99.9 Min	14 Hrs
J	.28 MM	.28 MM	.10 MM	0.00 MM	45.0 Min	0 Hrs
K	.28 MM	.28 MM	.10 MM	0.00 MM	45.0 Min	14 Hrs
L	.28 MM	.28 MM	0.00 MM	0.10 MM	99.9 Min	0 Hrs
M	.50 MM	.28 MM	.10 MM	0.00 MM	99.9 Min	0 Hrs
N	.28 MM	.50 MM	.10 MM	0.00 MM	99.9 Min	0 Hrs

Groups A through G were the test samples for the GM resin. Groups H through N were the test samples for the resin suggested by the SLA machine manufacturer.

PROCEDURES

TEST METHODS

The evaluation of the test specimens were conducted in accordance with ASTM guidelines. The method of testing was:

1) The tensile strength test (ASTM D638)

This method was used to measure the physical characteristics of the materials used. Specifically, to monitor the force necessary to pull the specimens apart, the amount that the material stretched before breaking.

INSTRUCTIONS

To solve the problem, the researcher divided the problem into seven phases. They were the following:

1) Review the SLA machine and materials
2) Prepare the SLA machine to run the GM material
3) Run test samples and cure for different lengths of time
4) Test specimens to find optimum results
5) Run the control situation (GM material)
6) Run the experimental situation (3-D material)
7) Test and evaluate the specimens

RECOMMENDATIONS

One variable that the researcher had no control over was the laser power of the SLA machine. The value varied from 9 to 21 mw. It would be interesting to see the relationship of the power value to the consistency of the parts. The laser loses power as the hours of use build up, then is strengthened by a set of commands.

FINDINGS

RESULTS

The results will be examined two ways. The first will be the different groups of the same resin will be compared and then the two resins will be compared to each other. Due to confidential information related to other experiments, the names of the resins will not be used in the reporting of the results. Therefore, the researcher will call them the GM resin and the 3-D resin, since 3-D Systems suggested the other resin.

The setup sheets are found in appendix B. The first column of each sheet can be ignored because it is for the support structure and has no bearing on the tensile test bars or the data collected. Groups A,B,H and I were the basic setting Delco Remy had been using before any experimentation. Groups A and H have the same settings the only difference was the material used. The same was true for groups B and I. Also in appendix B, there is the data collected for each test group from the tensile test with information on all the areas monitored with the mean, standard deviation, minimum, and maximum values displayed for each area. A single plot for each group is also found in appendix B which acts as an example for the group.

The GM resin Groups stretched between .0441 (Group F) and .1109 (Group A) inches. This is a fairly small amount to stretch before breaking. The peak load ranged from 322 pounds (Group C) to 540 pound (Groups F). The peak stress on the material was between 3748 psi (Group C) and 6616 psi (Group F). The tensile strength ranged from 1,740,000 psi (Group C) to 3,268,000 psi (Group F).

The 3-D resin Groups stretched from .2088 inches (Group K) and .3297 inches (Group J). The peak load varied from 242 pounds (Group K) to 286 pounds (Group H). The peak stress was between 3050 psi (Group K) and 3776 psi (Group H). The tensile strength varied 569,800 psi (Group I) and 1,724,000 psi (Group L).

CONCLUSIONS

It was apparent that by changing the settings the groups were very different. For all the GM resins, Group C seemed to be the worst. It was the lowest in peak load and stress as well as tensile strength. This group was the same as the basic settings except for the cure time which was half of the standard time. The best group from the aspect of tensile strength and peak load was Group F. This group used a Y-Hatch setting of .5 instead of .28 which was the normal setting.

For the 3-D resin, it was difficult to find a clearly best and worst group because the data was so close to each other from group to group. Group K was the lowest in stretch, peak load, and peak stress. This group had a 14 hour delay and a cure time of 45 minutes. Group H was the highest in peak load and peak stress and was in the mid-range for the tensile strength. Group H was a normal setting that Delco Remy used regularly.

SUGGESTIONS

The major differences seen in the two materials were the tensile strength and the displacement. It would be ideal to use the GM resin for parts which need higher tensile strengths and the 3-D resin for parts that need to be able to flex and stretch a greater amount. The setup for Group F produced the greatest tensile strength while Group J let the material stretch the largest amount. Due to the time involved to change the materials in the SLA machine it is impractical to change the material every time the other material is needed. The perfect situation would allow for quick interchangeable resin containers that would allow the resin to be changed in minutes instead of hours, but as of now there is no such system available.

The researcher understands that GM would rather use their own resin all the time, but when the tensile strength is compared along with the ability to stretch, the GM material is found not to be ideal for every situation. Also by looking at the totals for all the groups, the 3-D resin data is much more consistent than the GM resin. The standard deviations on the 3-D resin were much lower making the material more predictable.

BUDGET

	Requested From BSU	Delco Remy	Total
Supplies/Materials:			
4- 5 1/4 floppy disks	$6.00		$6.00
2 gallons of material		$600.00	$600.00
Equipment:			
40 hours of SLA machine @ $50/hour		$2000.00	$2000.00
10 hours of test equip. @ $30/hour		$300.00	$300.00
Travel:			
15 trips to Delco Remy @ 50 miles R.T. @ .25/mile	$187.00		
PROJECT TOTALS:	$193.50	$2900.00	**$3093.00**

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Apartment 2-D
Muncie, Indiana 47304
747-4120

APPENDIX A

Robbie Caudill
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Apartment 2-D
Muncie, Indiana 47304
747-4120

Friday March 20,1992

Mr. Steve Riley
Manager Process Engineer
Delco Remy: 18-214
Anderson, Indiana 46018

Mr. Riley,

I am sending you this letter to extend to you my gratitude for all you have done for me on my senior project. I thank you for letting me use your facility and equipment. I also thank you for all the literature you have shared with me about stereolithography. I am sure the information gathered from our experiment will benefit your future use of the SLA resins.

I appreciate the support and direction that you have gave me during the past several months. Thanks again!

Sincerely,

Robbie Caudill

Robbie Caudill
3905 North Chadam Lane
Apartment 2-D
Muncie, Indiana 47304
747-4120

Friday March 20, 1992

Mr. Bill Johnson
Physical Test Lab Technician
Delco Remy: 18-12
Anderson, Indiana 46018

Mr. Johnson,

I would like to take this time to say thank you for the help you gave me during my senior research project with the stereolithography resins. I appreciate the use of the Instron tensile test machine, as well as being so flexible about working me into the schedule to break the parts. I thank you for the information shared with me concerning tensile strength and proper testing procedures. Again, thank you very much!

Sincerely,

Robbie Caudill

Robbie Caudill
3905 North Chadam Lane
Apartment 2-D
Muncie, Indiana 47304
747-4120

Friday March 20,1992

Mr. Bob Claypool
Manufacture Engineer/SLA Technician
Delco Remy: 18-16F
Anderson, Indiana 46018

Mr. Claypool,

This letter is to recognize and commend your importance to my senior project. Without your help the project would have been impossible. I thank you for all you have done in having the parts ran in the stereolithography machine. Thanks again for all your help over that past months.

Sincerely,

Robbie Caudill

PRODUCT DATA SHEET SLA-250

STEREOLITHOGRAPHY APPARATUS

FUNCTION

StereoLithography, a process of creating three-dimensional plastic parts from CAD/CAM/CAE data, combines four technologies: laser, optical scanning, chemistry, and software.

Three-dimensional CAD/CAM/CAE data is processed to yield a series of cross sections by the SLA software. A HeCd laser generates an ultraviolet (UV) beam, which is moved across the surface of a vat of liquid photopolymer by a computer-controlled optical scanning system. The laser, as it draws each cross section, changes the liquid into a solid. A vertical elevator system lowers the newly-formed layer, while a recoating and leveling system establishes the next layer's thickness. Successive cross sections are built layer by layer, one on top of another, to form the complete object.

FEATURES

Fully automatic and unattended part building

Patented technology that interfaces with most popular CAD/CAM/CAE systems

Builds complex shapes, including interior features

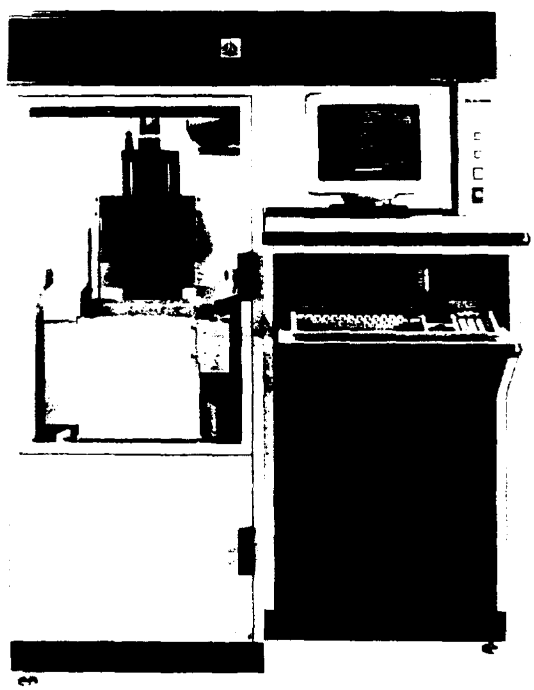
Has applications in many industries including automotive, aerospace, consumer products, electronic, computer, and medical

BENEFITS

Reduces time to market by accelerating the process of conceptual design and prototyping

Allows manufacturing to create first articles for producibility studies, tool and fixture design, and patterns for casting

Applications include conceptual designs, prototypes, and castings



Creates three-dimensional plastic parts from CAD/CAM/CAE data in a matter of hours, without tooling.

3D Systems, Inc.

OPTICAL	Beam spot size (working area) $(1/e)^2$	0.015 in/0.38 mm (max)
LASER	Type Wavelength Laser power (initial)	Helium Cadmium 325 nm 10 - 15 mW
SCANNING SYSTEM	Calibrated working area Step size (min) Spot location repeatability Drawing speed (max)	10 in x 10 in/254 mm x 254 mm 0.0003 in/0.008 mm ±0.0025 in/0.06 mm 15.0 inch/sec / 381 mm/sec
ELEVATOR SYSTEM	Vertical travel Vertical accuracy	14.0 in/356 mm ±0.0025 inch/0.06 mm
VAT	Part/platform size (max) Part weight allowed (max) Vat capacity	10 in x 10 in x 10 in 254 mm x 254 mm x 254 mm 20 lbs/9.1 kg 7.8 gallons/29.5 liters
RECOATING SYSTEM	Recoater blade speed (min/max) Layer thickness (min)	0.38 in/sec, 11.0 in/sec 9 mm/sec, 279 mm/sec 0.005 in/0.13 mm
LEVELING SYSTEM	Surface positional accuracy Surface positional repeatability	±0.001 in/0.03 mm ±0.001 in/0.03 mm
CONTROL SYSTEM	80286 processor, 10 MHz 80287 math coprocessor Monochrome graphic display	40 MB hard disk Floppy disk drive, 5.25", 1.2 MB LAN interface
Software	Proprietary software which monitors and controls the part building process	
SLICE COMPUTER	80386 processor Floppy disk drive, 5.25", 1.2 MB Ethernet interface	70 MB hard disk Monochrome display
Software	Proprietary software which cross sections formatted three-dimensional data UNIX Operating System	
ENVIRONMENT	Operating temperature Laboratory conditions	50°F - 79°F, ±1.8°F per hour 10°C - 26°C, ±1°C per hour

SAFETY

Process Chamber
Enclosed, with air recirculat[illegible] and charcoal filter

Laser shields and interlocks conform to Federal Performance Standard CFR21, Subchapter J.

SLA-250 meets all CDRH requirements for a Class I Laser product in normal operation, Class IIIb during field service.

DOCUMENTATION

SLA-250 User Reference Manual and Quick User Guide

OVERALL DIMENSIONS

Width, 49 in/1.24 m
Height, 65 in/1.65 m
Depth, 37 in/.94 m

SHIPPING DIMENSIONS

Uncrated
Width, 49 in/1.24 m
Height, 64.5 in/1.64 m
Depth, 27 in/.69 m

Shipping weight, (approx)
650 lb/295 kg

POWER REQUIREMENTS

115VAC ± 10%, 60Hz, 15A
or 220VAC ±10%, 50Hz, 8A
or 100VAC ±10%, 50/60Hz, 15A

Note: Specifications subjec[illegible] change without notice. 7000[illegible]
3/89

3D Systems, Inc.
26081 Avenue Hall
Valencia, CA 91355
(805) 295-5600
FAX (805) 257-1200

SLA-190 and 250 Users

Slice Resolution

Slice resolution converts .STL files from CAD space to Slice space by specifying the number of Slice units contained in each CAD unit.

Slice Resolution = number of Slice units per CAD unit (6,000 SU/CAD unit)

Slice units define an integer coordinate system within the Slice program, forming a three-dimensional grid, which is used to map an object from CAD space into Slice space.

Once sliced, the data is internally represented and manipulated in Slice units. Therefore, the object's geometry must be mapped to fit within the Slice space. See figure 4-2.

The maximum number of Slice units is 65,535. The largest X, Y, or Z coordinate of the CAD model determines the maximum acceptable value for Slice resolution. Increasing the Slice resolution will increase the fineness of the slice grid, improving the approximation of the object.

The highest Slice resolution can be calculated by dividing 65,000 by the largest coordinate value (X, Y, or Z) of the CAD model. In most cases, this value will not exceed 400 for millimeter parts or 10,000 for inch parts. Valid Slice resolutions ranges from 40 to 400 Slice units to the millimeter and 1000 to 10,000 Slice units to the inch.

All files comprising a single part (all support and object files belonging to a part) must be sliced with the same resolution.

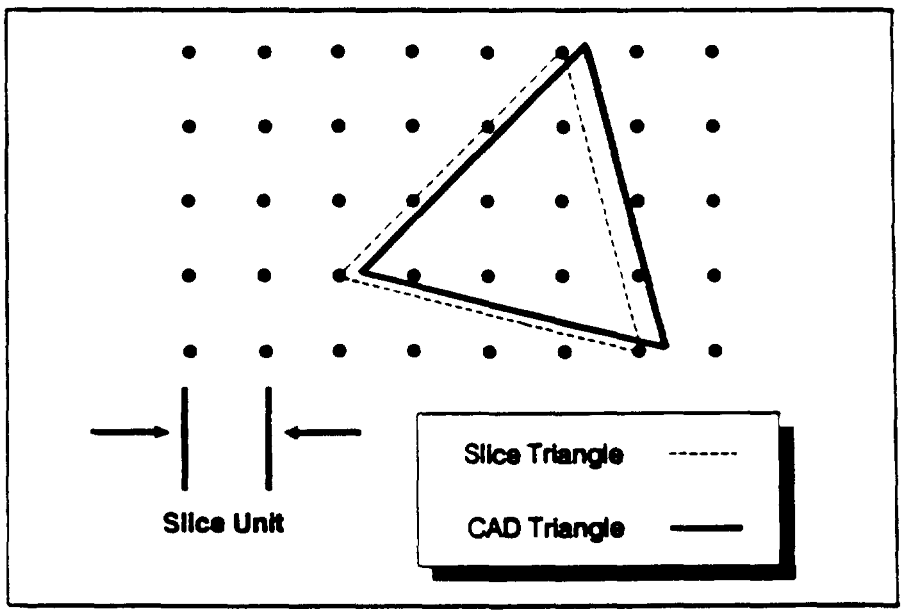


Figure 4-2. Slice Resolution

Layer Thickness

Layer thickness is a Slice parameter that allows users to specify the distance between vertical layers. This determines the vertical resolution and accuracy of the part which is limited to one layer thickness. Layer thickness directly effects the degree of "stair-stepping" when sloping (near flat) surfaces are approximated with horizontal and vertical surfaces. See figure 4-3.

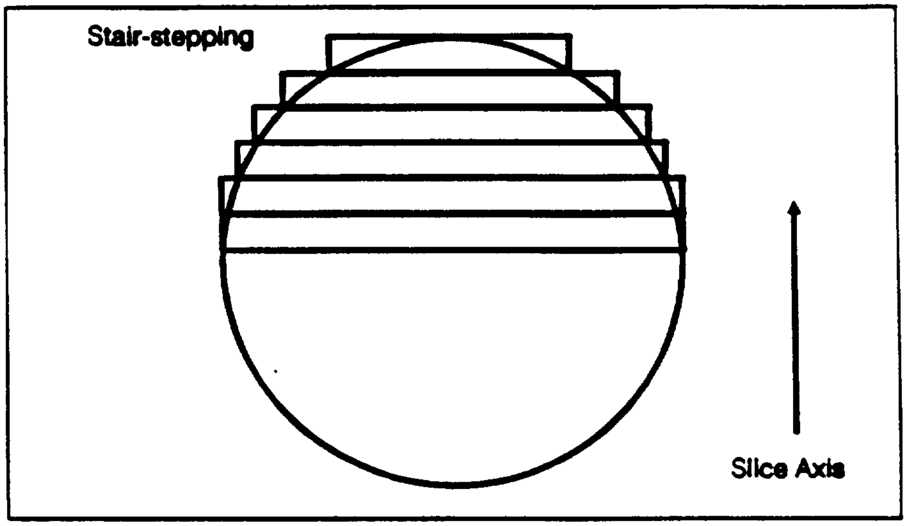


Figure 4-3. Stair-stepping Example.

Layer thickness also determines the height of each step. Decreasing the layer thickness in near flat regions results in a smoother surface, since the height of each step is reduced.

Thinner layers improve accuracy and the amount of detail in the vertical direction, however, much more data is created. Thicker layers can be used to strengthen parts, however, the laser must trace at a slower rate.

Layer thickness may be fixed for an entire file (all layers assigned the same layer thickness) or varied (groups of layers having different layer thickness).

Data Representation

Triangles

The StereoLithography surfaces or solids are represented by triangles. The conversion from the CAD representation to triangles is made by a process called tessellation, which mathematically divides surfaces into planar facets or triangles.

Many CAD and solid modeling systems represent surfaces of parts as facets for graphic display. Triangles, the simplest polygon, can closely approximate all surfaces. A rectangle can be represented by two triangles, while curved surfaces can be closely approximated using a large number of triangles.

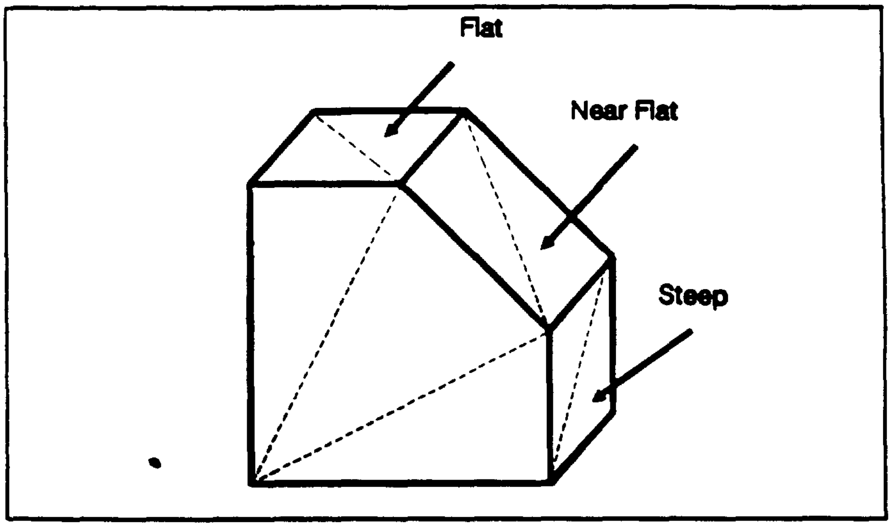


Figure 4-4. Triangle Classification

The software defines three types of triangles: flat, near flat, and steep. See figure 4-4. Based on the orientation of the CAD model, these triangle categories determine how the vectors are generated to represent the surfaces needed to build the part.

Minimum Surface Angle

StereoLithography file triangles that are inclined at an angle between the specified Minimum Surface Angle (MSA) and horizontal (0 degrees) are classified as near flat. For these triangles, the Slice program places skin fill vectors inboard of the boundary vectors defined by these near flat triangles. See figure 4-5 below where θ represents the angle of the part.

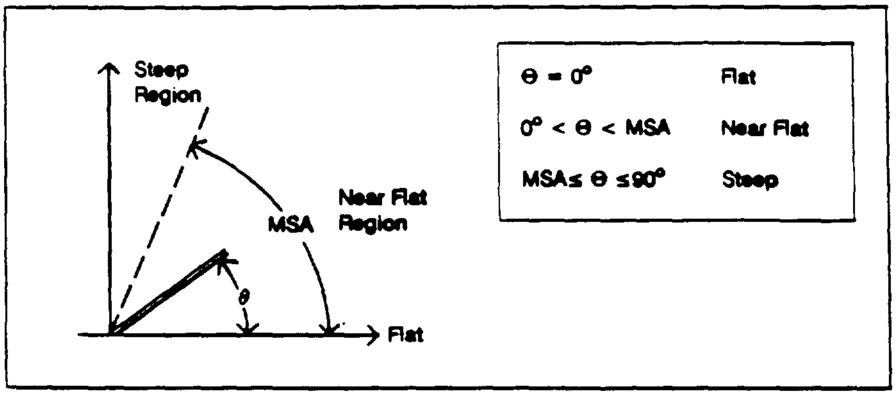


Figure 4-5. MSA Definition

When a boundary vector overlaps the boundary vector of the layer directly below it, no skin fills are required at that point to seal in the uncured resin within the part. The width of the cured boundary vector is determined by the actual laser beam diameter and the cure depth.

The Slice program determines the angle between boundary vectors and checks the MSA setting to determine if near flat skin fills are required. If the boundary vectors are overlapping, the MSA should be set at an angle less than the angle of the triangle. MSA Example 1, figure 4-6, shows overlapping boundary vectors not needing skin fill, when the MSA is set at less than 50°.

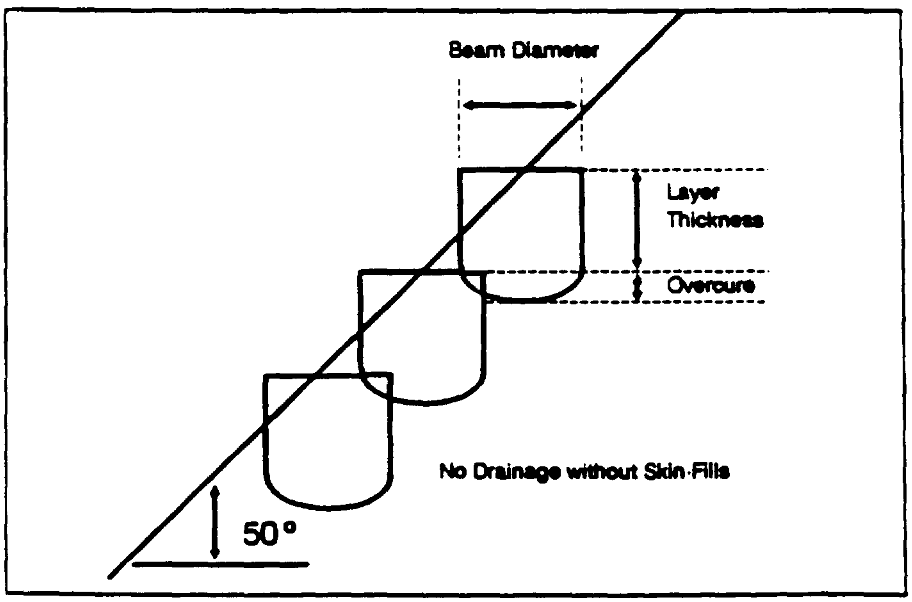


Figure 4-6. MSA Example 1

If the MSA is set at a lesser angle than recommended for a given layer thickness, skin fills are not generated for some areas that might require the fills. The fills are required to avoid resin from draining. MSA Example 2, figure 4-7, shows that no skin fill is generated for layers at a 40° angle when the MSA is set to less than 40°.

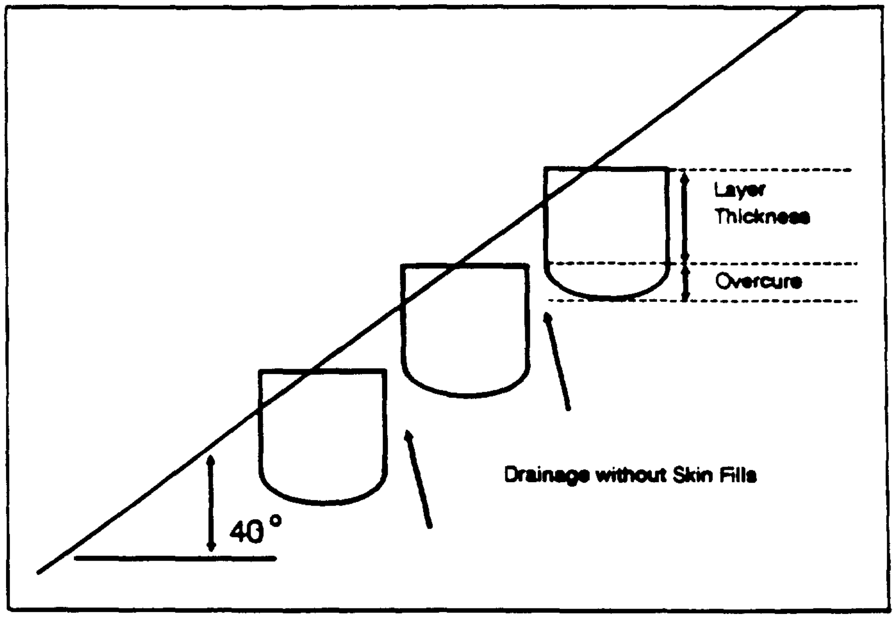


Figure 4-7. MSA Example 2

If the MSA is set greater than the recommended value for a given layer thickness, it causes Slicing to generate more skin fill vectors than necessary, increasing the run time and file size. MSA Example 3, figure 4-8, shows skin fill vectors being generated that are not needed when the MSA is set above 40°.

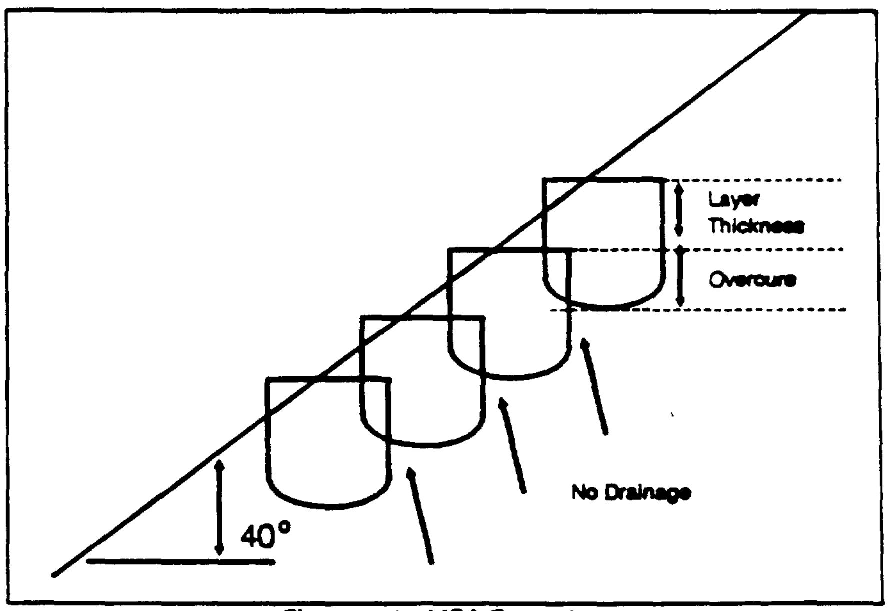


Figure 4-8. MSA Example 3

Vectors

Vectors are very small lines that are traced by the laser to create the plastic part. When triangles are sliced, three types of vectors are created to define the surface boundaries and internal structure on a layer-by-layer basis: layer borders, cross hatches and skin fill vectors. See figure 4-9.

Layer Borders

These vectors define vertical surface boundaries (walls).

Cross Hatch

These vectors form an internal grid structure created to strengthen walls and maintain structural integrity, while entrapping liquid in the area between layer borders. The spacing between cross hatches and the hatch directions are user-defined. When building a part using the WEAVE™ technique, the spacing between hatch vectors is only slightly greater than a cured linewidth.

Skin Fill

These vectors define horizontal (top and bottom) surfaces. They are a series of closely spaced parallel vectors that form a skin when drawn by the laser.

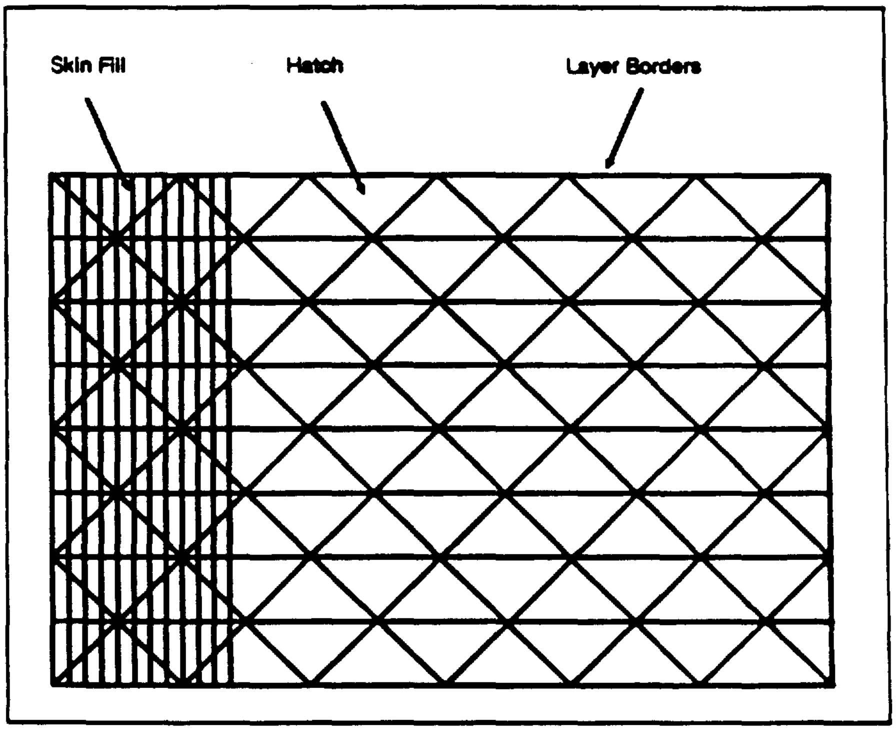


Figure 4-9. Types of Vectors

Vector Blocks

Slice creates vector blocks for a variety of two end-point vectors. The block identifiers follow the mnemonic rule:

First character set	=	Type of triangle
Second character	=	Type of surface
Last character	=	Type of vector

a-ding the memory

Mnemonic Description

LB	Layer border
LH	Layer hatch
FUB	Flat up border
FUF	Flat up skin fill
FDB	Flat down border
FDF	Flat down skin fill
NFUB	Near flat up-skin border
NFUF	Near flat up-skin fill
NFDB	Near flat down-skin border
NFDH	Near flat down-skin hatch
NFDF	Near flat down-skin fill

The block identifiers include a numeral after the mnemonic to identify the merge set to which the vectors belong. Refer to page 4-39 for a definition of the term "merge set".

EXAMPLE: FUF2

Beam Width Compensation

Slice software uses an enhanced line width compensation (Beam Comp.) algorithm to improve part accuracy.

This option is used to adjust the border vectors inward (away from the surface normal). The distance the border vectors should be adjusted inward is equal to half the width of the cured line segment. A line width of .010 in (typical for a cure depth of 0.016 in) will have a –cure of .005 in. As cure depth increases, line width increases due to additional exposure.

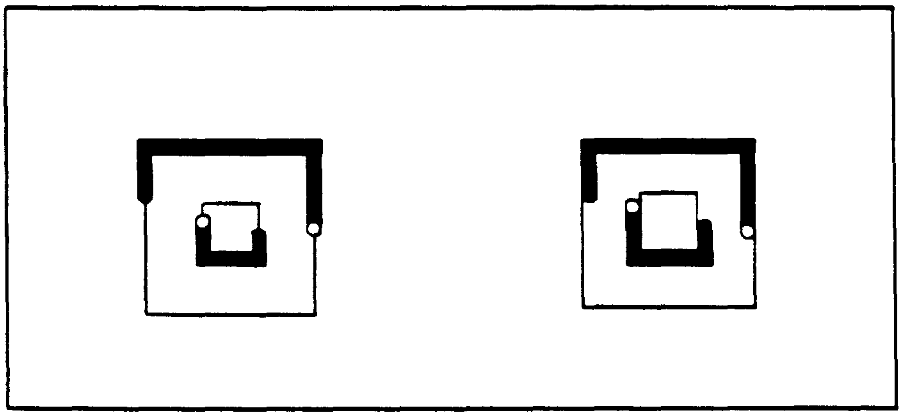


Figure 4-10. Beam Width Compensation Example

EXAMPLE 1:

An inch part with a beam compensation value of .006 in moves the border vectors inward toward the solid volume of the part, in the XY plane by 0.006 in.

The simple cross section in figure 4-10 above shows how a hole, or interior border vectors, and the exterior border vectors are treated. The hatch vectors are automatically adjusted accordingly.

EXAMPLE 2:

A metric part (mm) with a beam compensation value of 0.15 mm moves the border vectors inward by 0.15 mm.

Note

Due to extra processing, Slice takes longer when using the beam compensation option.

After slicing is completed, a warning message indicates that a number of bytes of memory have not been freed. The user need not worry about the danger of exceeding memory requirements, however, since slicing results in only a small amount of unfreed memory with both small and large parts.

Memory used during slicing is freed after the Slice program is exited.

Data Structure

After the .STL files have been sliced to create the Slice (.SLI) files, the Slice files are merged to create the four part building data files: .PRM, .V, .R, and .L. These are the actual files used by Build to produce the StereoLithography part.

Figure 4-11 on the following page gives an overview of the basic part building data structure.

Resolution

PURPOSE:	Specifies the Slice resolution.
TYPE:	2 *(enter key)* to choose Resolution.
PROMPT:	**Enter resolution value:**
TYPE:	n *(enter key)* where n specifies the Slice resolution (number of Slice units per CAD unit).
USE:	Divides CAD space into smaller Slice units creating a three-dimensional grid.
EXAMPLE:	Using a Slice resolution of 5000 for a CAD model defined in inches, divides each inch of the part into 5000 Slice units, so that each Slice unit equals 0.0002 inches.

Note

A rounded number resolution value (n), such as 100, 200, or 5000, is usually chosen.

The default value is 5000 for inch parts and 200 for millimeter parts.

The range for inch parts is 1000 to 10000 and 40 to 400 for millimeter parts.

Use the highest value possible, but check that the maximum coordinate value of the CAD model (.STL triangle vertex in the X,Y,or Z plane) multiplied by the resolution is less than or equal to 65535.

Do not offset any file so that its maximum extent, multiplied by the Slice resolution, is greater than the 65535 limit.

Slice resolution must be the same for all merged parts.

Layer Thickness

PURPOSE: Defines the vertical distance between layers, in CAD units.

TYPE: 3 *(enter key)* to choose Layer Thickness.

PROMPT: **Fixed or Variable Layer Thickness (F, V or X)?**

TYPE: [f, v, or x] *(enter key)*

EXAMPLE: Type 0.01 *(enter key)* to design a part to be built with layers 0.01 in thick.

Note

Variable layer thickness allows sets of layers (in vertical ranges) to be created with different layer thicknesses.

Thinner layers are commonly used to minimize the stair-step effect on sloping surfaces and improve accuracy of critical vertical dimensions and details.

Thicker layers are used to strengthen unsupported regions, produce stronger, more rigid layers, or decrease part building time.

Fixed

PURPOSE: Specifies the value of the layer thickness, which will be the same throughout the height of the part.

TYPE: f *(enter key)* to set Fixed Layer Thickness.

PROMPT: **Fixed Layer Thickness Value?**

TYPE: n *(enter key)* where n is the layer thickness value, entered in CAD units.

Typical values range from 0.50 to 0.125 mm (0.005 to 0.020 in).

Type	Thickness	
Fine	0.125 mm	(0.005 in)
Medium	0.25 mm	(0.010 in)
Coarse	0.50 mm	(0.020 in)

Variable

PURPOSE: Specifies the layer thickness that varies throughout the part, and assigns the values and the vertical height that take effect in a Variable Layer Thickness Table.

TYPE: v *(enter key)* to set Variable Layer Thickness.

PROMPT: **Command (Add [level]** *(spacebar)* **[thickness], Delete [level], Save, eXit, Help)?**

EXAMPLE: To have a layer thickness of .010 in from the bottom of an object to 2 inches in CAD space, and a thickness of .005 in to the top of the object, type:

a0 *(spacebar)* **.010** *(enter key)*. The zero defaults to the bottom of the part.

a2 *(spacebar)* **.005** *(enter key)*. This thickness remains unchanged through to the completion of the part.

Incorporating different layer thicknesses in a part is useful for isolating detailed regions. Use the following guidelines when slicing one .STL file with more than one layer thickness.

1. First break point (level) must be zero.
2. At each break point, the larger layer thickness must be evenly divisible by the smaller.
3. All break points must be a multiple of the coarsest layer thickness at that point.
4. All layer thicknesses in a Z level must be evenly divisible by the smallest layer thickness there.
5. If using a scale factor in Slice (Alter option 1), multiply all break points by the scale factor.

Add

PURPOSE: Adds an entry to the Variable Layer Thickness Table to specify a vertical height and corresponding layer thickness.

TYPE: a [**level**] *(spacebar)* [**thickness**] *(enter key)*
where **level** is the Z level value that starts in or below the part and **thickness** is the layer thickness starting at that level. Specifiying a level below the bottom of the part causes the specified thickness to start at the bottom or first layer of the part.

Typical values range from 0.125 to 0.50 mm (0.005 to 0.020 in).

Type	Thickness	
Fine	0.125 mm	(0.005 in)
Medium	0.25 mm	(0.010 in)
Coarse	0.50 mm	(0.020 in)

Note

A thickness of zero causes the prompt to repeat.

There are no default variable layer thickness values.

Save *must be executed at this point to retain the variable layer thickness information.*

Slicing continues at the specified spacing until another layer thickness is defined, or the top of the part is reached.

The user must specify a minimum of two entries to produce variable slicing of an object.

Delete

PURPOSE: Removes an entry from the Variable Layer Thickness Table.

TYPE: d [level] *(enter key)* where **level** is the Z level value and corresponding layer thickness to be removed.

Note

If input level does not match an existing level, an error message is displayed. If no level is input, the previously added level is deleted.

Save

PURPOSE: Saves the Variable Layer Thickness Table.

TYPE: s *(enter key)* to save the Variable Layer Thickness Table.

USE: Writes the Variable Layer Thickness Table into memory and returns to the Alter Menu.

Note

Updates table in memory, but does not permanently save it on disk.

Exit

PURPOSE: Exits the Variable Layer Thickness Table.

TYPE: x *(enter key)* to exit the Variable Layer Thickness Table.

Note

Returns user to the Alter Menu without saving the Variable Layer Thickness Table in memory, or to disk, unless the Save comand (above) was used.

Help

PURPOSE: Displays a help message for the Variable Layer Thickness Table options.

TYPE: **h** *(enter key)* to access Help.

X Hatch Spacing

PURPOSE: Specifies the distance between cross hatch vectors drawn parallel to the X axis.

TYPE: **4** *(enter key)* to set X hatch spacing.

PROMPT: **Enter X hatch spacing value (hx):**

TYPE: **hx** *(enter key)* where **hx** is the distance, in CAD units, between cross hatches drawn parallel to the X axis.

The range of values for **hx** are from 0.0 to 13.0 mm (0.0 to 0.5 in).

Note

Inputting a zero generates no X cross hatch.
The default is 0.28 mm (0.011 in).

Negative numbers are interpreted as positive.

Use zero for web supports, since web supports designed as two back-to-back, vertical surfaces do not need cross hatches.

A combination of X and Y cross hatch forms a rectangular grid for WEAVE™.

Use X and 60/120 cross hatches to create a structure of equilateral triangles.

Y Hatch Spacing

PURPOSE: Specifies the distance between cross hatch vectors drawn parallel to the Y axis.

TYPE: 5 *(enter key)* to set Y hatch spacing.

PROMPT: **Enter Y hatch spacing value (hy):**

TYPE: **hy** *(enter key)* where **hy** is the distance, entered in CAD units, between cross hatches drawn parallel to the Y axis.

The range for **hy** is 0.0 to 13.0 mm (0.0 to 0.5 in).

Note

Inputting a zero generates no Y cross hatch. The default is 0.28 mm (0.011 in).

Negative numbers are interpreted as positive.

Use zero for web supports, since web supports designed as two back-to-back, vertical surfaces do not need cross hatches.

A combination of X and Y cross hatch forms a rectangular grid for WEAVE™.

60/120 Degree Angle Hatch Spacing

PURPOSE: Specifies the distance between parallel cross hatch vectors drawn at 60 and 120 degrees from the X axis.

TYPE: 6 *(enter key)* to set 60/120 degree hatch spacing.

PROMPT: **Enter a value for 60 to 120 degree angle hatch spacing:**

TYPE: n *(enter key)* where n is the distance, entered in CAD units between cross hatches drawn at 60° and 120° from the X axis.

The range of values for n is 0.0 to 13.0 millimeters (0.0 to 0.5 in). Typical angle hatch spacing values are 0.6 to 2 mm (0.009 to 0.075 in).

Note

WEAVE™ and STAR-WEAVE™ are the recommended build styles to achieve the most accurate parts and the best part finish.

Inputting a zero generates no 60/120 cross hatch, and is the default if no value is entered.

Negative numbers are interpreted as positive.

Use zero for web supports, since web supports designed as two back-to-back, vertical surfaces do not need cross hatches.

Use X and 60/120 cross hatches to create a structure of equilateral triangles.

X Skin Fill Spacing

PURPOSE: Specifies the distance between skin fill vectors drawn parallel to the X axis.

TYPE: 7 *(enter key)* to set X skin fill spacing.

PROMPT: **Enter X skin fill spacing value (hfx):**

TYPE: **hfx** *(enter key)* where **hfx** is the distance in CAD units.

Typical fill spacing values are 0.076 to 0.127 mm (0.003 to 0.005 in).

Note

Inputting a zero generates no skin vectors.

Negative numbers are interpreted as positive.

Do not use both X and Y fill at the same time or deformation of surfaces may occur.

Use zero for supports.

Specify the skin fill along the axis that is most practical for the geometry of the part.

Y Skin Fill Spacing

PURPOSE: Specifies the distance between skin fill vectors drawn parallel to the Y axis.

TYPE: 8 *(enter key)* to set Y skin fill.

PROMPT: **Enter Y skin fill spacing value (hfy):**

TYPE: **hfy** *(enter key)* where **hfy** is the distance in CAD units.

Typical fill spacing values are 0.076 to 0.127 mm (0.003 to 0.005 in).

Note

Inputting a zero generates no skin vectors, and is the default if no value is entered.

Negative numbers are interpreted as positive.

Do not use both X and Y fill at the same time or deformation of surfaces may occur.

Use zero for supports.

Specify the skin fill along the axis that is most practical for the geometry of the part.

Minimum Surface Angle for Scanned Facets

PURPOSE: Specifies the angle at which horizontal skins are created to fill gaps between vertical walls.

TYPE: 9 *(enter key)* to set minimum surface angle for scanned facets.

PROMPT: **Enter a Minimum Surface Angle value (MSA):**

TYPE: **n** *(enter key)* where **n** is the recommended MSA value in degrees.

The correct MSA depends on the layer thickness specified.

The following table provides the recommended values.

Layer Thickness		MSA
mm	*in*	*degrees*
0.125	0.005	40
0.25	0.010	50
0.375	0.015	55
0.50	0.020	60

Note

Use zero for supports.

The system accepts values of 0° to 90°.
If no value is entered, the default is 50°.

Negative values are interpreted as positive.

Staggered Hatch

PURPOSE: To reduce internal stress that accumulates during the Build process.

TYPE: **10** *(enter key)* to toggle on and off.

Alternate Sequencing

PURPOSE: To normalize stress directions by using a composite layering technique.

TYPE: **11** *(enter key)* to toggle on and off.

Retracted Hatch

PURPOSE: To reduce internal stress by retracting the end point of each vector so that is does not bond with the border vector.

TYPE: **12** *(enter key)* to toggle on and off.

Slice Output File Name

PURPOSE: Specifies the name for the Slice file (.SLI) output.

TYPE: **13** *(enter key)* to set Slice output file name.

PROMPT: **Enter new slice output file name:**

TYPE: **[file name]** *(enter key)* to enter a Slice file name.

Note

File name should be eight characters or less.

The default file name is the same as the .STL file name.

Enter file name prefix only; the .SLI extension is assumed.

The output .SLI file is a binary file.

Slice Resolution

PURPOSE:	Specifies the slice resolution.
PROMPT:	**Slice Resolution 40 to 400 millimeters (1000 to 10000 inches) CAD units**
TYPE:	**n** *(enter key)* where **n** specifies the Slice resolution (number of Slice units per CAD unit).
USE:	Divides CAD space into smaller Slice units creating a three-dimensional grid.
EXAMPLE:	Using a Slice resolution of 5000 for a CAD model defined in inches divides each inch of the part into 5000 Slice units, so that each Slice unit equals 0.0002 inches.

Note

A rounded number resolution value (n), such as 100, 200, or 5000, is usually chosen.

The default value is 200 for millimeter parts and 5000 for inch parts.

The range for inch parts is 40 to 400 for millimeter parts and 1000 to 10000.

Use the highest value possible, but check that the maximum coordinate value of the CAD model (STL triangle vertex in the X,Y, or Z plane) multiplied by the resolution is less than or equal to 65535.

Do not offset any file so that its maximum extent, multiplied by the Slice resolution, is greater than the 65535 limit.

Slice resolution must be the same for all merged parts.

Layer Thickness

PURPOSE: Defines the vertical distance between layers, in CAD units.

PROMPT: **Layer Thickness can be Fixed or Variable; use spacebar to toggle**

TYPE: *(spacebar)* to toggle.

Note

Variable layer thickness allows sets of layers (in vertical ranges) to be created with different layer thicknesses.

Thinner layers are commonly used to minimize the stair-step effect on sloping surfaces and improve accuracy of critical vertical dimensions and details.

Thicker layers are used to strengthen unsupported regions, produce stronger, more rigid layers, or decrease part building time.

Layer Thickness: Fixed

PROMPT: **Layer Thickness 0.0635 to 0.50 millimeters (0.0025 to 0.020 inches)**

TYPE: n *(enter key)* where n is the layer thickness value, entered in CAD units.

Typical values range from 0.125 to 0.50 mm (0.005 to 0.020 in).

Type	Thickness
Fine	0.125 mm (0.005 in)
Medium	0.25 mm (0.010 in)
Coarse	0.50 mm (0.020 in)

Layer Thickness: Variable

PURPOSE: Specifies the layer thickness that varies throughout the part, and assigns the values and the vertical height that take effect in a Variable Layer Thickness Table.

PROMPT: **Enter Start Layer in CAD Units**

TYPE: n *(enter key)* where n is 0 for the first break point.

PROMPT: **Enter Layer Thickness in CAD Units**

TYPE: n *(enter key)* where n is the first layer thickness in CAD units. The range is 0.0635 to 0.50 mm (0.0025 to 0.020 in).

PROMPT: **Enter Start Layer in CAD units**

TYPE: n *(enter key)* where n is the break point in CAD units for the beginning of the next layer thickness.

PROMPT: **Enter Layer thickness in CAD units**

TYPE: n *(enter key)* where n is the next layer thickness in CAD units. The range is 0.0635 to 0.50 mm (0.0025 to 0.020 in).

EXAMPLE: To have a layer thickness of .010 in from the bottom of an object to 2 inches in CAD space, and a thickness of .005 in to the top of the object, type:

0 *(enter key)* .010 *(enter key)*. The zero defaults to the bottom of the part.

2 *(enter key)* .005 *(enter key)*. This thickness remains unchanged through to the completion of the part.

Incorporating different layer thicknesses in a part is useful for isolating detailed regions. Use the following guidelines when slicing one .STL file with more than one layer thickness.

1. First break point (level) must be zero.
2. At each break point, the larger layer thickness must be evenly divisible by the smaller.
3. All break points must be a multiple of the coarsest layer thickness at that point.
4. All layer thicknesses in a Z level must be evenly divisible by the smallest layer thickness there.
5. If using a scale factor in Slice (Alter option #1), multiply all break points by the scale factor.

Note

A thickness of zero causes a prompt with the available range to display.

There are no default variable layer thickness values.

Slicing continues at the specified spacing until another layer thickness is defined, or the top of the part is reached.

The user must specify a minimum of two entries to produce variable slicing of an object.

X Hatch Spacing

PURPOSE: Specifies the distance between the cross hatch vectors drawn parallel to the X axis.

PROMPT: **X Hatch Spacing 0.025 to 25.0 millimeters (0.001 to 1.0 inches), 0 to disable**

TYPE: n *(enter key)* where n specifies the X Hatch Spacing.

Note

Inputting a zero generates no X cross hatch. The default is 0.28 mm (0.011 in).

Use zero for web supports, since web supports designed as two back-to-back, vertical surfaces do not need cross hatches.

A combination of X and Y cross hatch forms a rectangular grid for WEAVE™.

Y Hatch Spacing

PURPOSE: Specifies the distance between adjacent cross hatch vectors, drawn parallel to the Y axis.

PROMPT: **Y Hatch Spacing 0.025 to 25.0 millimeters (0.001 to 1.0 inches), 0 to disable**

TYPE: **n** *(enter key)* where **n** specifies the Y Hatch Spacing.

Note

Inputting a zero generates no Y cross hatch, and is the default if no value is entered.

Use zero for web supports, since web supports designed as two back-to-back, vertical surfaces do not need cross hatches.

A combination of X and Y cross hatch forms a rectangular grid for WEAVE™.

60/120 Degree Hatch Spacing

PURPOSE: Specifies the distance between parallel cross hatch vectors drawn at 60 and 120 degrees from the X axis.

PROMPT: **60/120 Degree Hatch Spacing 0.025 to 25.0 millimeters, (.001 to 1.0 inches), 0 to disable**

TYPE: **n** *(enter key)* where **n** is the distance, entered in CAD units, between cross hatches drawn at 60° and 120° from the X axis.

Note

Inputting a zero generates no 60/120 cross hatches.

Use zero for web supports, since web supports designed as two back-to-back, vertical surfaces do not need cross hatches.

Use of X and 60/120 cross hatches to create a structure of equilateral triangles.

X Skin Fill Spacing

PURPOSE: Specifies the distance between skin fill vectors, drawn parallel to the X axis.

PROMPT: **X Skin Fill Spacing 0.025 to 0.25 millimeters (0.001 to 0.01 inches), 0 to disable**

TYPE: **n** *(enter key)* where **n** specifies X Skin Fill Spacing.

Note

Inputting a zero generates no skin vectors.

Typical fill spacing values are 0.076 to 0.127 mm (0.003 to 0.005 in).

Do not use both X and Y fill at the same time or deformation of surfaces may occur.

Use zero for supports.

Specify the skin fill along the axis that is most practical for the geometry of the part.

Y Skin Fill Spacing

PURPOSE: Specifies the distance between skin vectors, drawn parallel to the Y axis.

PROMPT: **Y Skin Fill Spacing 0.025 to 0.25 millimeters (0.001 to 0.01 inches), 0 to Disable**

TYPE: **n** *(enter key)* where **n** specifies Y Skin Fill Spacing.

Note

Inputting a zero generates no skin vectors, and is the default if no value is entered.

Typical fill spacing values are 0.076 to 0.127 mm (0.003 to 0.005 in).

Do not use both X and Y fill at the same time as deformation of surfaces may occur.

Use zero for supports.

Specify the skin fill along the axis that is most practical for the geometry of the part.

Minimum Surface Angle

PURPOSE: Specifies the angle at which horizontal skins are created to fill gaps between vertical walls.

PROMPT: **Minimum Surface Angle 0 to 90 degrees**

TYPE: **n** *(enter key)* where **n** specifies Minimum Surface Angle.

The correct MSA depends on the layer thickness specified.

The following table provides the recommended values.

Layer Thickness mm	Layer Thickness in	MSA degrees
0.125	0.005	40
0.25	0.010	50
0.375	0.015	55
0.50	0.020	60

Note

Use zero for supports.

The system accepts values of 0° to 90°.
If no value is entered, the default is 50°.

Beam Compensation

PURPOSE: To adjust the border vectors inward (away from the surface normal). The distance the border vectors should be adjusted inward is equal to half the width of the cured line segment. Refer to pages 4-9 and 4-10.

PROMPT: **Beam Compensation 0.025 to 0.5 millimeter (0.001 to 0.02 inches); 0 to disable**

TYPE: **n** *(enter key)* where **n** specifies Beam Compensation.

Note

Beam compensation moves the boundaries towards the solid volume of the part.

The typical offset is half of the beam diameter.

Slice Axis	PURPOSE:	Specifies the axis to slice.
	PROMPT:	**Select Slice Axis [Z/Y/X]; spacebar to toggle**
	TYPE:	*(spacebar)* to toggle.

Note

It is recommended that parts be oriented and sliced along the Z axis.

Staggered Hatch	PURPOSE:	To reduce internal stress that accumulates during the build process by drawing every other layer of X and Y vectors offset a distance equal to half the hatch spacing. This means that X and Y vectors from the second layer will not be scanned directly on top of X and Y vectors of the first layer.
	PROMPT:	**Staggered Hatch: Offset hatch line every other layer; spacebar to toggle**
	TYPE:	*(spacebar)* to toggle on and off.
Alternate Sequencing	PURPOSE:	To normalize stress directions by using a composite layering technique. The order and direction in which the hatch vector are scanned is alternated for each layer.
	PROMPT:	**Alternate Sequencing: Alternate X and Y hatch vectors and propagation directions; spacebar to toggle**
	TYPE:	*(spacebar)* to toggle on and off.
Retracted Hatch	PURPOSE:	To reduce internal stress by retracting the end point of each vector so that is does not bond with the border vector. Only the starting point of the hatch vectors bond to the border vectors.
	PROMPT:	**Retracted Hatch: Attach hatch line to only one border; spacebar to toggle**
	TYPE:	*(spacebar)* to toggle on and off.

Setup and Build

Overview

StereoLithography is made possible by a process called photopolymerization in which a liquid resin is converted to a solid polymer upon exposure to ultraviolet light. The degree to which polymerization occurs, and thus the solidity of the material, is dependent on the total light energy absorbed.

The polymerization of resins is not a new technology. It has been used in such applications as ultraviolet inks, coatings, varnishes, and printed circuits for more than twenty years. However, the use of lasers as the light energy source is a more recent innovation.

Photopolymers

The photopolymers used in StereoLithography are composed of two basic materials. The first is a photoinitiator which absorbs the laser energy and forms reactive radical species, which initiate the polymerization process. The photopolymers also contain acrylic functionalized monomers and oligomers, which polymerize upon exposure to a free radical source.

Totally UV-curable polymers do not appreciably polymerize when heated after being cured by the laser, but in the liquid form can polymerize uncontrollably when overheated.

The preceding discussion of photopolymers, and the following discussion of the photopolymerization process, provide only a basic overview. Detailed information on both topics can be found in the following reference: *UV Curing, Volumes I and II:* Editor, S. Peter Pappas, Science and Technology Marketing Corp., Norwalk, Connecticut (1980).

Photopolymerization Process

The sequence of events in the photopolymerization process are explained in the following section. See figure 5-1.

Photoinitiators

Photoinitiator molecules (PI) absorb UV light from the laser and are converted to an excited state (the singlet state $^1PI^*$). This short-lived, high energy species quickly relaxes to a lower energy excited state (the triplet state $^3PI^*$).

Primary Radicals

The excited $^3PI^*$ molecules catalyze formation of one or more (generally one) species called primary radicals (R), with the formation reaction and number dependent on the photoinitiator used.

Polymer Chain

The primary radical reacts with an acrylic monomer (M) to form a new radical species (RM). This starts a chain propagation process (polymerization) in which the reaction is repeated over and over again to form a polymer chain.

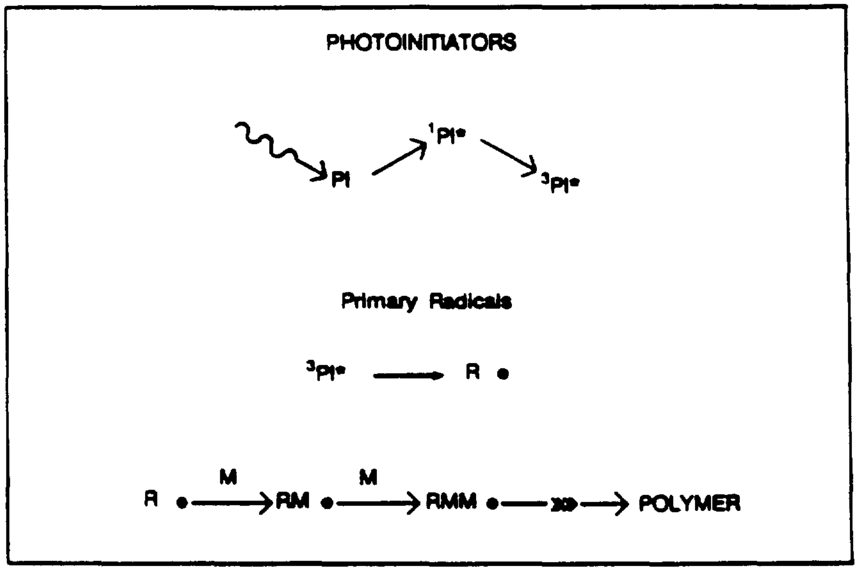


Figure 5-1: Photopolymerization Process

Solidification

The polymer quickly increases in molecular weight until it is evident as a solid. The reaction quickly stops if the light energy is removed through a variety of termination mechanisms. The reaction will slow down and eventually stop as the available monomer concentration decreases in the exposed regions. The overall dimensions of the solid polymer, formed when a UV laser is focused on the surface of a photopolymer, are controlled by the intensity of the laser beam and the period of exposure. A longer exposure or increased laser energy increases the depth and width of the solidified region.

Influencing Factors

A relatively small change in temperature can cause a large change in the viscosity of the resin. Higher temperatures and reduced viscosity result in thinner liquid that settles faster during dipping and drains faster during post processing. However, higher temperatures also result in more "voids" or "dimples", increased swelling, and decreased green strength.

The best results are obtained by working within the temperature range specified for a given resin. Oxygen in the air acts to inhibit the photopolymerization process by interacting with the photoinitiator and terminating the chain. The combination of these effects creates a "threshold" of minimum exposure that is needed to support photopolymerization.

Creating Solid Plastic

Bullets

During the build process, a stationary UV laser beam, focused on the surface of the photopolymer, solidifies (cures) a small volume of liquid into the shape of a bullet. See figure 5-2.

The intensity profile of the laser beam varies from point-to-point with the maximum intensity being closest to the center of the beam. As the laser beam strikes the surface, a quantity of light is absorbed (polymerizing the liquid) while a portion is transmitted to the liquid below it. Therefore, the overall dimensions are determined by how much laser energy enters the liquid. This quantity of laser energy is known as exposure.

Since the degree of polymerization is proportional to the amount of light absorbed, the surface area of the resin is the most solid, and the area below the surface hardens in proportion to the amount of light energy absorbed.

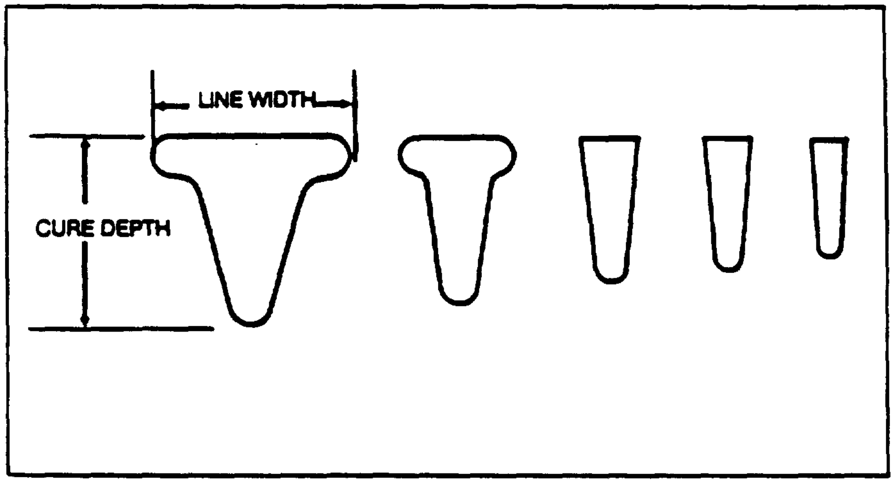


Figure 5-2. Plastic Bullet Shapes

Cure Depth

The depth of the cured plastic increases as the exposure of light increases and therefore varies across the width of the laser beam, since the beam cross section is not uniform as shown by the intensity profile in figure 5-3 on the next page. Thus, the center of the beam cures to the greatest depth because it is the area of highest intensity, and the surrounding areas cure to lesser depths. The maximum solid depth achieved (after laser exposure) is known as the cure depth.

Stereolithography utilizes two methods of defining cure depth values: overcure and cure depth. Overcure is the amount of cure applied over or under the layer thickness. Cure depth is an absolute value and has no direct correlation to layer thickness. Overcures are applied to border and hatch vectors which form the framework of the part and are dependent on layer thickness. Cure depth values are applied to skin fill vectors only (flat and near flat facing up and down vectors). Skin fills are used to fill in flat or horizontal surfaces, not to bond layers of resin together, thus layer thickness is not utilized in cure depth calculations.

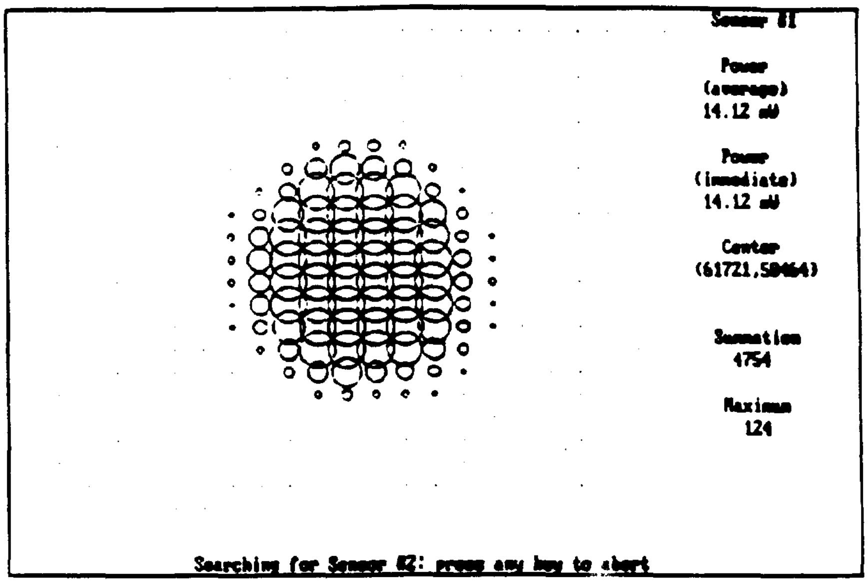


Figure 5-3. Laser Beam Cross Section

Step Periods

Bullets are the building blocks of StereoLithography. The overlap of successive bullets forms lines that overlap to form surfaces. To form lines, the laser beam is moved in steps or increments. After each step, the laser remains stationary for a given period of time. This time, plus the brief transit time required to move to the next location, is known as the step period. A step period is measured in units of 10 microseconds.

In addition to varying the dimensions of the bullets, large step period values affect the shape of the bullets.

Step Size

Bullets overlap to form lines. The distance the laser moves between forming bullets is a parameter known as step size. If the step size is less than or equal to the maximum diameter of the bullets (i.e., measured across the top of the bullet), the bullets overlap and a continuous line is formed.

Note

Step periods and step sizes are transparent to the user.

Bonding and Overlap

To adhere or bond the top layer with the previous one below it, the cure depth must be greater than the slice thickness by a layer overlap or overcure factor. This additional cure depth is the overcure amount. See figure 5-4 on the following page.

Layer-to-layer bonding occurs when the UV light of the laser, curing the current layer, penetrates down to the previous layer to form chemical bonds between the lower layer and the newly formed top layer.

Strong layer-to-layer bonding, created by the required overlap, is needed to build strong parts. However, an excessive overlap causes layers to deform and curl.